A VERIFICATION LIBRARY FOR MULTIBODY SIMULATION SOFTWARE

Sung-Soo Kim and Edward J. Haug
The Center for Simulation and Design Optimization of Mechanical Systems
The University of Iowa
Iowa City, Iowa 52242

Harold P. Frisch
NASA Goddard Space Flight Center
Greenbelt, Maryland 20771

Abstract

A multibody dynamics verification library, that maintains and manages test and validation data is proposed, based on RRC Robot arm and CASE backhoe validation and a comparative study of DADS, DISCOS, and CONTOPS that are existing public domain and commercial multibody dynamic simulation programs. Using simple representative problems, simulation results from each program are cross checked, and the validation results are presented. Functionalities of the verification library are defined, in order to automate validation procedure.

1. Introduction

Multibody simulation software programs are currently used for an extremely broad range of applications; e.g., robotics, space structures, automotive vehicles, farm machinery, spacecraft, etc. Most multibody programs in active use have passed an exhaustive series of theoretical tests. However, none have been subject to the rigors of an extensive laboratory test and validation program. A project supported by NASA has been established to validate and evaluate multibody simulation programs through experimental testing and theoretical cross checking, so that engineers can utilize simulation software with confidence. Moreover, through this validation and evaluation procedure, modeling and analysis capabilities that must be developed can be identified for future code enhancements.

To carry out validation for current and future flexible multibody simulation programs, there is a need to define and to perform a series of laboratory tests that can be used as references. There is also a need to set up a library of test and validation data that are maintained in a format that is compatible with input and output data requirements of commercially available and public domain multibody simulation programs.

The verification procedure envisioned involves (1) defining actual mechanical systems and tests, (2) performing the series of tests, (3) modeling the mechanical systems, (4) simulation and test data processing, and (5) comparison between simulation data from different software and experimental data for validation. To alleviate the engineer's burden in modeling, simulation, and data post-analysis, a systematic tool; i.e., a verification library system, is being developed to automate the verification procedure by integrating software modules to store models, launch simulation software, and manage data.

To develop this verification library system requires (1) a survey of multibody simulation software to investigate modeling and analysis capability and at the same time to identify a standard input and output data format for the verification library, (2) theoretical cross verification among simulation software and validation of multibody programs with generic multibody problems through experimental tests, and (3) definition of engineering capabilities for the verification library system, based on experience obtained from tasks (1), and (2).

The purposes of this paper are the to (1) present current verification activities, based on a comparative study of the flexible multibody simulation programs DADS, DISCOS, and CONTOPS and validation of those programs through theoretical cross checking and experimental testing, and (2) to define a verification library system; i.e., its functionality and software architecture. Note that DADS, DISCOS and CONTOPS are multibody simulation software that treat flexible body components and have integrated capabilities for simulation of the mechanical subsystems and the control subsystems. In Section 2, current validation activity is presented. Section 3 presents a summary of current multibody simulation capabilities. Finally, the concept of the verification library system is defined in Section 4.

2. Current Validation Activities and Status

2.1 Validation of Manipulator System

Manipulator arms have been chosen as generic multibody problems, since they are actively controlled variable kinematic topology systems, when the end effector contacts ground, and their joints have nonlinear effects such as friction and flexibility. Two manipulator systems have been simulated and tested for verification. One is the RRC (Robot Research Corporation) robot arm and the other is a CASE construction backhoe.

The RRC arm shown in Fig. 1 has 7 revolute joints, each with a harmonic drive gear transmission. This arm is actively driven by DC servo-motors with position, velocity, and torque feedback controllers. Due to the high gear ratio of the harmonic drive, effective rotor inertia effects and gyroscopic forces are significant.
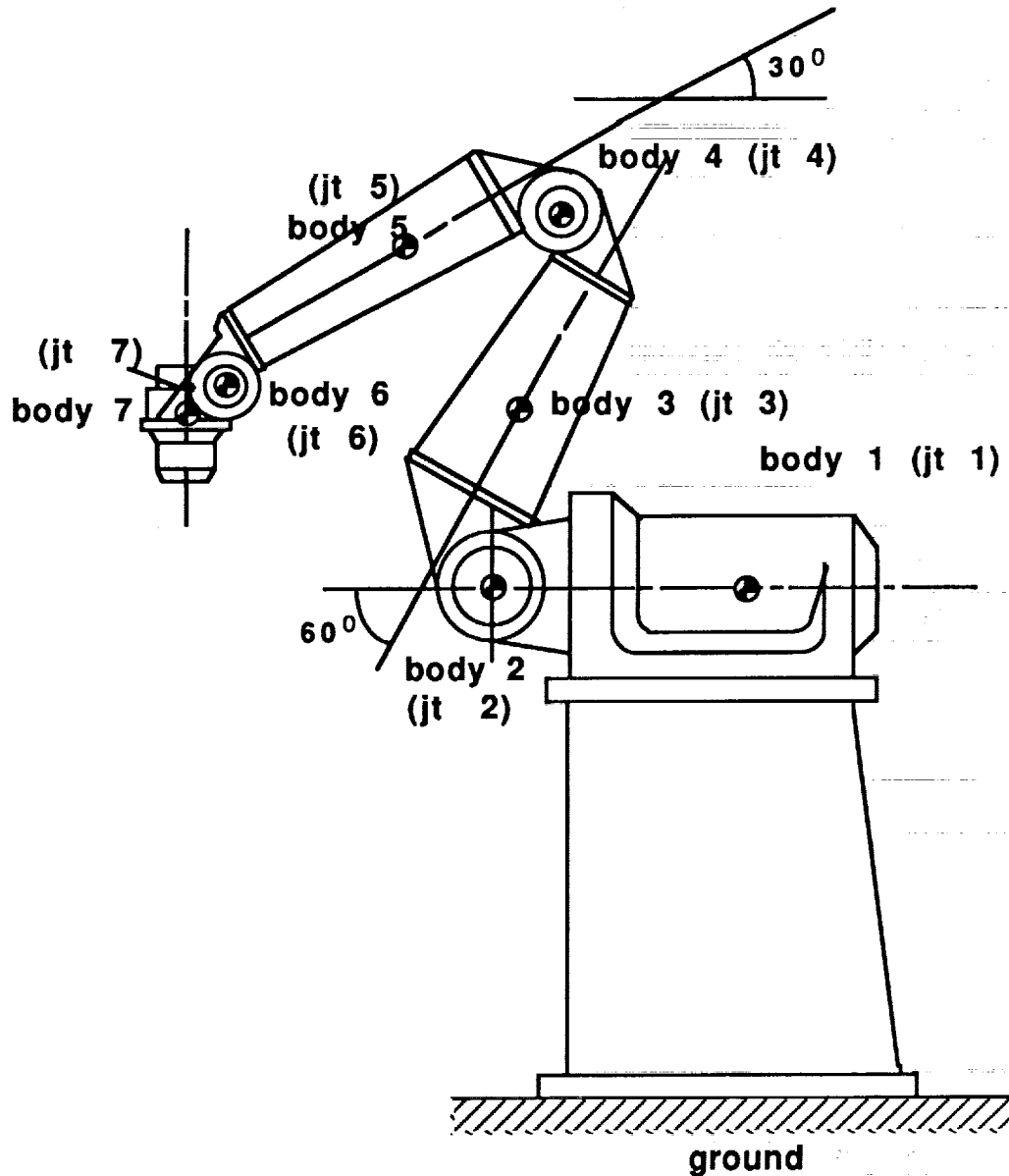

Figure 1. RRC Robot Arm

Several simple and moderately complicated experimental tests have been performed at NASA Goddard robotics laboratory. Test data have been collected and processed, to be compared with simulation results. RRC arm simulation models have been created with different degrees of fidelity, according to inclusion of the gear reducer, friction, and joint controllers, using DADS and the Order N Iowa program [1,2]. Validation of the dynamic and dynamic/control simulation is under way. For dynamics validation, experimentally obtained joint control torques have been imposed in the simulation model. Joint displacements and velocities from experiments and simulations can thus be compared. In this way, dynamic simulation can be isolated from dynamic/control simulation. For dynamic/control validation, the same controller reference input is imposed in the simulation model to obtain displacement, velocity, and control torque of each joint, to be compared with experimental data. Details will be presented in Ref. 3.

The CASE backhoe system is manipulated by hydraulic actuators and consists of topological closed loops. Joint frictions are important dynamic effects. A simulation model has been created using the DADS program. Piston displacements and forces in hydraulic actuator have been validated through experimental tests. Static strains of several interest points in the boom has been also validated. Detailed validation results are presented in Ref. 4.

2.2 Theoretical Cross Verification with DADS, DISCOS, and CONTOPS

To validate multibody simulation codes such as DADS, DISCOS, and CONTOPS by cross checking simulation results, four representative simple multibody problems were selected; i.e., rigid body open and closed systems and flexible body open and closed loop systems. Since details are presented in Refs. 5-9, only validation results are summarized in this paper.

As a simple rigid body open loop multibody problem, the double pendulum system shown in Fig. 2 was simulated with all three programs. Springs and dampers are attached to joints 1 and 2. The simulation was carried out under the influence of gravitational force in negative y direction. All of three programs generated essentially the same solution.
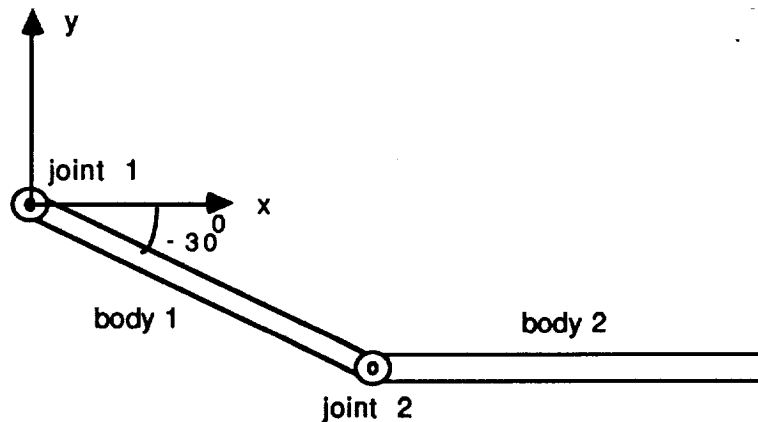

Figure 2. Double Pendulum

As a rigid body closed loop multibody problem, the four bar linkage mechanism shown in Fig. 3 was cross validated. Springs and dampers are mounted at joints 1 and 4. Under the influence of gravitational force in the negative y direction, simulations were carried out. Since the DISCOS program cannot handle rigid body closed loop systems, cross verification was done only between DADS and CONTOPS, which yielded the same simulation results.
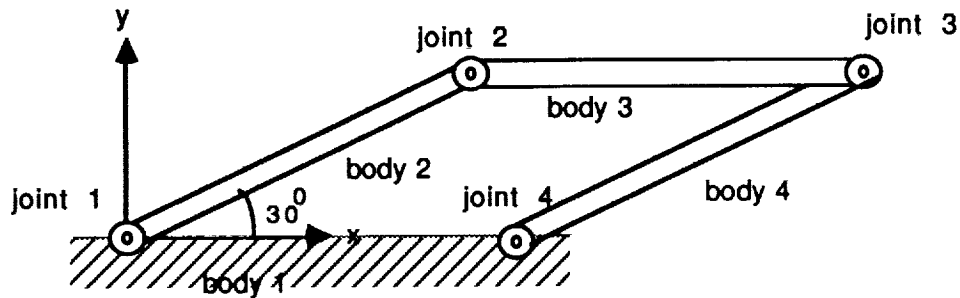
Figure 3. Rigid Four Bar Linkage

As a flexible open loop multibody problem, a flexible beam that are attached to a moving body was tested. A schematic diagram of the flexible beam is presented in Fig. 4. Body 2 rotates about the z axis with constant angular velocity. The flexible beam is initially deformed. In order to represent flexibility of the beam, the first two vibrational normal modes with clamped boundary conditions were employed. Simulations were carried out without gravitational force. Since CONTOPS has no provision for imposing a pre-strained initial configuration, only DADS and DISCOS were cross validated. Essentially the same results were obtained with both codes.
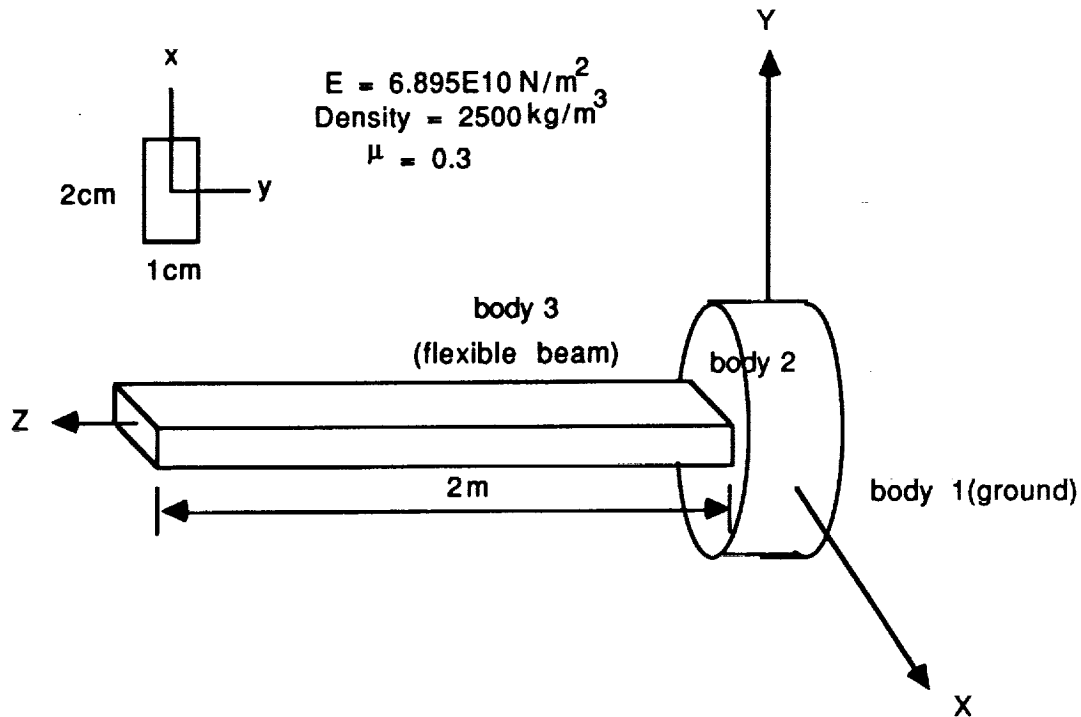

Figure 4. Rotating Flexible Beam

A four bar linkage with a flexible coupler was tested, as shown in Fig. 5. It is difficult to use CONTOPS program for this application, since the user must provide time independent coefficient terms related to the flexible body [9], and no provision is made for imposing initial modal coordinates and rates. Thus, only DADS and DISCOS simulations were carried out, without gravity force. Since the DISCOS program requires at least 6 vibrational modes for any closed loop system, six vibrational modes including an axial direction mode were used to represent flexibility of the coupler. Gross motion and dominant deformation motion (lateral bending) were the same for both DADS and DISCOS solutions. However, slightly different results were obtained in axial motion of the coupler. With a moderate integration step size, DISCOS generated axial motion values that were approximately the average of the oscillatory motion values obtained by DADS. With a smaller integration step

size, the axial motion values of DISCOS tended to converge with those of DADS. Thus, DISCOS required a small integration step size, in order to produce the same results as DADS.
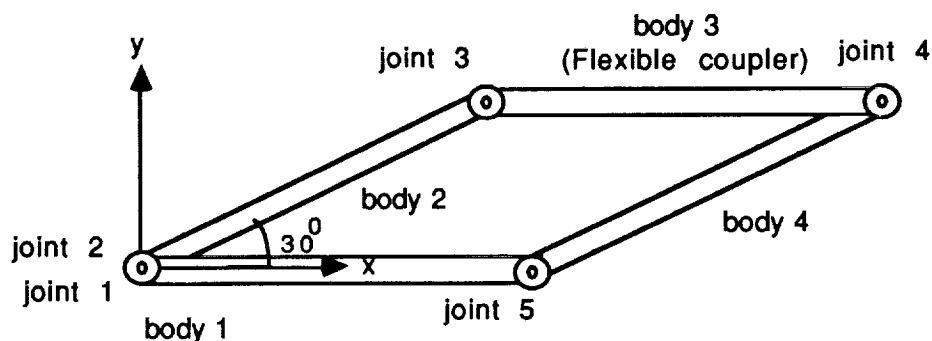

Figure 5. Flexible Four Bar Linkage

3. Current Status of Multibody Simulation Software

A comparative study [10] has been made among the simulation codes such as DADS, DISCOS, and CONTOPS, based on the experience of theoretical cross verification. These three programs are the first candidate simulation software to be validated for verification library. Difficulties in defining standard data for verification library, such as simulation and test data and their format were identified through this comparative study. This comparative study illustrates modeling and analysis capabilities of each simulation code.

3.1 Generality

The current multibody simulation programs are biased to generic problem classes. Thus, modeling and analysis capabilities of each code are different. DADS has been developed for dynamics of mechanisms and ground vehicles, whereas DISCOS and CONTOPS are spacecraft oriented. Thus, there are several differences in modeling and analysis approaches. DADS handles closed loop mechanical systems such as ground vehicle suspensions and mechanisms as easily as open loop systems. In DISCOS, to solve a closed loop system, at least one flexible body with at least six vibrational normal modes must be employed to satisfy loop closure constraint equations. Since CONTOPS uses relative coordinates, the user must specify cut joints to generate a spanning tree system. However, only spherical joints can be cut. Thus, DISCOS and CONTOPS are somewhat limited in treating closed loop mechanical systems.

DADS provides six standard joints (bracket, revolute, universal, spherical, cylindrical, and translational joints) and several non-standard joints (revolute-revolute, revolute-translational joints etc). Most of joints represent physical objects encountered in mechanisms and machines. They are treated as passive joints that transmit motion and force from one body to the adjacent body, thus active controllers are attached only to revolute joints. In DISCOS and CONTOPS, general joints that can have from 0 to 6 relative degrees of freedom are used and any generalized coordinate associated these joints can be actively controlled.

DADS provides a library of force elements such as springs, dampers, actuators, and a user defined force element. In addition to these basic force elements, there are vehicle oriented force elements such as tire force, leaf spring, and bushing elements. A rotational spring, damper, and actuator element is applicable in any revolute or cylindrical joint. A translational spring, damper, and actuator can be defined between pairs of bodies. DISCOS offers several different kinds of user subroutines to compute force in a system. Springs and dampers can be attached in general joints along any joint coordinate. The translational spring and damper can only be attached to a translational joint. CONTOPS also provides spring and damper elements for joints. Translational springs and dampers are also available between pair of bodies.

Gyrostats (momentum wheels) are often used for attitude control of satellites. Thus, DISCOS provides gyrostats that can be attached to any body without introducing extra-bodies. However, in DADS and CONTOPS, extra-bodies must be introduced with a revolute joint and a driver to make an equivalent model.

CONTOPS provides a library of sensor elements that are related to spacecraft dynamics, such as sun and star sensors. Modeling capabilities are summarized in Table 1.

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Table 1. Modeling Capabilities of DADS, DISCOS, and CONTOPS for Dynamic Simulation

	DADS	DISCOS	CONTOPS
Type of Motion	Spatial/Planar	Spatial	Spatial
Body Type	Rigid/Flexible	Rigid/Flexible	Rigid/Flexible
Gyrostat	No	Yes	No
Joint Type	Library	General	General
Topology	Open/Closed	Open/Closed(flex)	Open/Closed(limited)
Initial Assembly	Yes	No	No
Force Element	Library	RSD1, TSD2(Joint), user	RSD1, TSD2(s)
Gravity	Yes	Yes (user)	Yes
Driver	Library	Joint	Library
Sensor	Point of interest	Sensor	Library
Curve Element	Yes	No (user)	Yes
Reaction Force	Yes	Yes	Yes

1. Rotational-spring-damper.   2. Translational-spring-damper.

The DADS program can perform kinematic, dynamic, and inverse dynamic analyses, whereas DISCOS and CONTOPS can only treat dynamic analysis. Since DADS and DISCOS use Cartesian coordinates in forming the equations of motion, sparse matrix solvers for linear equations are used to obtain accelerations. In contrast, CONTOPS uses relative joint or abstract coordinates to form state space equations of motion (the number of equations of motion is the same as the number of degrees of freedom), and a full matrix solver is used for solving linear equations.

Analysis capabilities and formulation methods for these three dynamic simulation codes are summarized in Table 2.

Table 2. Analysis Capabilities of DADS, DISCOS, and CONTOPS

	DADS	DISCOS	CONTOPS
Analysis Mode	$K^1/D^2/ID^3$	D^2	D^2
Linearization	Yes	Yes	Yes
Formulation	Virtual Work	Lagrange Eq.	Kane's Eq.
Coordinate Systems	Cartesian	Cartesian	abstract/joint
Identification Igc^4, dgc^5	Yes	No	No
Linear Equation Solver	Sparse Matrix	Sparse Matrix	Full Matrix
Constraint Force	Yes	Yes	Yes
Speed-Up Options	No	No	Yes
Integrator	$A(v)^6$	$RK(f)^7$	$RK(f)^7, A(v)^6, U^8$
CPU Time Report	Yes(binary output)	Yes	No
Restarting Options	No	No	Yes

1. Kinematic analysis
2. Dynamic analysis
3. Inverse dynamic analysis
4. Independent generalized coordinates
5. Dependent generalized coordinates
6. Adams Bashforth and Adams Moulton variable order and variable step method
7. Runge Kutta fourth order constant step method
8. User provide integration method

3.2 Ease of Use and Code Automation

DADS, DISCOS, and CONTOPS have alpha-numeric interactive pre- and post-processing capabilities. The post-processor provides basically x-y plots. An interactive pre-processor helps the user to define necessary input

data. However, it is difficult for the user to find mistakes in input data for complicated spatial mechanical systems. Some graphics oriented user interfaces are provided by DADS for post-analysis and animation.

Flexible body dynamic analysis can be carried out with each of these three programs. Data associated with flexible body components can be obtained from finite element analysis. DADS provides interfaces with NASTRAN and ANSYS. DISCOS and CONTOPS can be integrated with NASTRAN.

DADS uses a variable order-variable step integration method. Step size is automatically selected by the program, according to the system characteristic of the equations of motion. Thus, the user does not need to choose step size. DISCOS uses a constant step Runge Kutta fourth order method. Thus, the user must have an idea of how small a step size is required for a certain mechanical system simulation. CONTOPS can have three different integration methods, such as a constant step Runge Kutta fourth order method, an Adams family variable step method, and a user defined integration method.

Imposing initial conditions on a closed loop system is challenging, since generalized coordinates and velocities in closed loop systems are not independent. A kinematically admissible initial state of the mechanical system must be imposed. DADS provides initial assembly and initial velocity computation routines, so that from user's initial estimate of the configuration and definition of initial conditions, a mechanical system is assembled to satisfy all kinematic relations. However, DISCOS and CONTOPS require the user to provide kinematically consistent initial conditions, which can be difficult for complicated closed loop systems.

In order to use current multibody simulation codes, a dynamics work station [11] is being developed to automate dynamic simulation modeling and post-processing by integrating a graphics oriented modeler, an initial assembly program, finite element codes, a graphics oriented post-processor, and an animator.

3.3 Input and Output

In order to systematically compare the simulation data from different simulation software with experimental data from a validation library, it is important to study input and output data definition for each program, to identify standard data for the verification library. Input data for each code are dictated by the formulation used. Since Cartesian coordinates are used in DADS and DISCOS, and interrelationships between pair of bodies due to joints are treated as constraints, there is no concept of inboard, outboard, base bodies, and cut joints. However, for CONTOPS, these are necessary data for its relative joint coordinate approach.

The flexible body formulation in each code studied is based on lumped mass and modal coordinate approaches. Thus, most data required to define flexible bodies are the same. However, CONTOPS does not need a lumped mass matrix. Instead, it requires the user to provide a so called h-parameter array [9], which is function of nodal masses and mode shapes. Such parameters are internally computed with given nodal masses and mode shapes in DADS and DISCOS.

The items required to describe a body and a joint are essentially the same for each code. However, the way a conceptual item is defined is quite different. For example, in order to define a joint triad, DADS and CONTOPS require the user to specify two unit vectors of the joint triad with respect to the body reference frame, whereas DISCOS requires Euler angles for the triad.

An input data comparison is summarized in Table 3.

Table 3. Input Data Comparison among DADS, DISCOS, and CONTOPS.

Body data

	DADS	DISCOS	CONTOPS
Initial Position & Orientation	Yes	No	No
Inertia properties	Centroidal/Body frame	Body frame	arbitrary
Nodal Coord.	Yes	Yes	Yes
Nodal Mass	Yes	Yes	No
Nodal Inertia	No	Yes	No
Modal Stiffness	Yes	Yes	Yes
Modal Damping	No	Yes	Yes
Modal Mass	Yes	No	Yes
Mode Shapes	Eigen/Static Vector	Shape function	Shape function

Topology data

	DADS	DISCOS	CONTOPS
Base Body	No	Yes	Yes
Inboard/Outboard Body	No	No	Yes
Cut Joint	No	No	Yes

Joint data

	DADS	DISCOS	CONTOPS
Joint Type	Library	General	General
Joint position/Velocity	No	Yes	Yes
Joint Reference Frame	P, Q, R	X, Y, Z, Euler angles	Direction cosine vector

Initial condition data

DADS	Initial independent coordinates and velocities
DISCOS	Initial relative coordinates and velocities
CONTOPS	Initial relative coordinates and velocities

Output data that represent physical quantities are different for each code. DADS provides the position and orientation of the body with respect to an inertial reference frame. However, DISCOS reports body center of mass position with respect to the first body reference frame (a kind of reference body for the mechanical system). Translational velocity of a body is reported in an inertial reference frame in DADS, whereas it is reported in body reference frames in DISCOS. DISCOS also reports total linear and angular momentum of the system and each body's contribution to total kinetic and potential energy.

An output data comparison is presented in Table 4.

Table 4. Comparison of output data among DADS, DISCOS, and CONTOPS

	DADS	DISCOS	CONTOPS
Body Positions	Yes	Yes	No
Body Orientations	Yes	Yes	No
Body Velocities	Yes	Yes	No
Body Accelerations	Yes	Yes	No
Modal Coordinates	Yes	Yes	Yes
Modal Velocities	Yes	Yes	Yes
Modal Accelerations	Yes	Yes	No
Relative Displacements	No	Yes	Yes
Relative Velocities	No	Yes	Yes
Relative Accelerations	No	No	No
Constraint Forces	Yes	Yes	Yes
Sensor Frame Positions	Yes	Yes	Yes
Sensor Frame Velocities	Yes	Yes	Yes
Sensor Frame Accelerations	Yes	Yes	Yes
Position of System C.M.	No	Yes	No
Total Momentum	No	Yes	No
Total Energy	Yes	Yes	No

4. Verification Library System

4.1 Verification Procedure

The conceptual verification procedure is presented in Fig. 6. Through parameter estimation for the mechanical system, system parameters can be defined for the model. At the same time, experimental tests can be defined, identifying what kind of physical quantities can be measured through experimental test, according to the availability of measuring devices. From this test plan, simulation model initial conditions and simulation scenarios can be defined. Simulation input data for a particular simulation code can then be set up, with initial condition, simulation scenario, and mechanical system parameter such as geometric dimensions, and inertia properties.

Experimental tests can be performed and data for measurable physical quantities can be acquired, according to the test plan and availability of measuring devices. Experimental test data are then processed and investigated to determine whether they are meaningful.

Simulations can be carried out according to simulation scenarios defined. The simulation data associated with observable physical quantities are extracted from the simulation output data. Through x-y plots, simulation and experimental data can be compared. Engineers can then evaluate simulation results. If simulation results are quite different from experimental results, the engineer can refine the simulation model. With the refined model, the mechanical system can be re-analyzed. An evaluation report for a validated multibody simulation can then be provided.

The test plan, observable physical quantities, and processed test data, simulation input and output data, and the evaluation report are then stored for reference.

4.2 Verification Library System Functionality

In Subsection 4.1, a conceptual verification procedure is introduced. However, this verification procedure may involve tedious data preparation and manipulation effort. For example, If an engineer wants to validate his simulation, he can set up the simulation model by retrieving the test plan and simulation input data for previously validated simulation software. He must understand previous simulation input data, which may not be easy. After carrying out a simulation, results can be compared by retrieving test data and evaluation reports from the verification library. The engineer should provide simulation data that have compatible format with existing experimental data.

In order to alleviate these burdens, a verification library system is desired, which can automate following procedures; modeling, carrying out simulations, and storing and retrieving data for verification of the multibody simulation software. For systematic verification, several functionalities are being considered for the verification library. The first functionality of the verification library system is to store and retrieve the following data; test plan, observable physical quantities, processed test data, simulation input and output data, and the associated evaluation report. The second functionality is to model a mechanical system for different simulation programs. Using a graphics oriented mechanical system modeler, a neutral input that contains generic mechanical system data can be created and modified. Neutral input data can be translated into input data for DADS, DISCOS, CONTOPS, and other multibody simulation programs. The third functionality is to launch simulation software to obtain simulation results. An interface program is required to integrate the verification library system and simulation software. The fourth functionality is to display simulation and experimental results together, using computer graphics, to help in the evaluation procedure. The final functionality is to create and edit evaluation reports.

To achieve these functionalities (engineering capabilities), software integration [12] is required. The verification library system being designed will integrate a dynamics workstation, x-y plots, visualization software [13], and the simulation codes DADS, DISCOS, and CONTOPS with a database management system. A schematic of the verification library system is presented in Fig. 7.
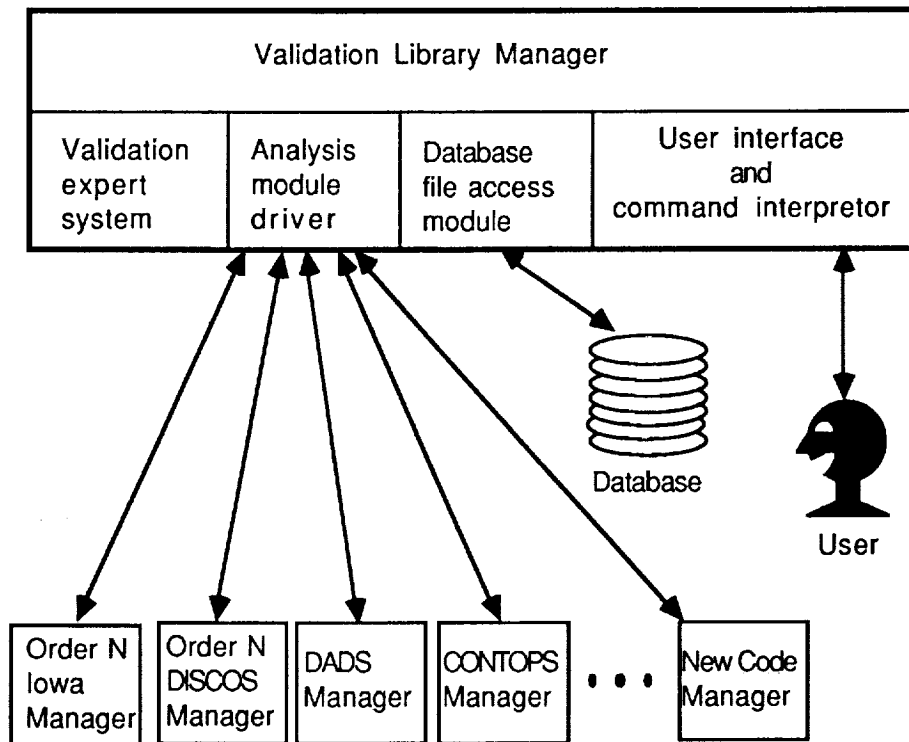
Figure 6. Validation Procedure Data Flow

Figure 7. Verification Library Software Architecture

5. Conclusions

The verification library system concept and engineering requirements have been introduced based on experience gained in RRC arm and CASE backhoe validations and theoretical cross verifications of DADS, DISCOS, and CONTOPS. A systematic software integration technique will be utilized to achieve an integrated capability to help potential users to validate their multibody simulation software.

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